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## New Zealand climate: patterns of drought 1941/42 – 2012/13

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### Abstract

Drought is important for agriculture and water resources in New Zealand, despite New Zealand's maritime location, drought does occur. New Zealand's complex orography gives distinctive regional climatic responses to variations in atmospheric circulation. Thus drought tends to be regional in extent. By utilising an index of agricultural drought (accumulated potential evapotranspiration or PED), rotated principal components (RPC) are used to define five spatially coherent regions. The RPC scores are used for describing variability in drought for the period 1941-2013. The regions are large: northern areas of the North Island, the east of the South Island, southern New Zealand, and the west of the North Island and the north of the South Island. Drought seasons in the five regions were all associated with the persistence of distinct patterns of atmospheric circulation, typically when anticyclones were more frequent. Conversely wetter seasons occurred generally when there were more troughs than usual. Four of the five regions show a distinct trend towards higher values of drought indices over the 72 year period, associated with higher austral summer pressures in the New Zealand region linked to Southern Hemisphere stratospheric ozone depletion.

### 1. Introduction

Globally, the IPCC (Seneviratne, et al. 2013) concluded that there is medium confidence that some regions of the world have experienced a trend to more intense and longer droughts (southern Europe and West Africa) and in some regions droughts have become less frequent, less intense, or shorter (central North America and northwestern Australia) since the 1950s. In New Zealand, droughts have occurred over the decades and have been a source of economic stress and hardship. Impacts on the New Zealand economy have been severe. For example, the 1997/98 El Niño drought had a major impact on New Zealand agriculture. The New Zealand Institute of Economic Research estimated that the associated drought resulted in a loss of \$618 million

(0.9%) to GDP (Gardiner, 2001). This was caused by a decline in agricultural production due to less livestock production, lower livestock weights, higher feed costs and other associated impacts (Gardiner, 2001). Compared with other natural climatic hazards, droughts are normally the most costly climatic extreme economically. Other droughts notable for their economic impact resulted in the hydroelectricity crisis of 1992, and the Auckland water supply crisis of 1994. The recent 2012/13 drought also depressed GDP by 0.7-0.9% (Ministry of Primary Industries, 2013; NIWA, 2013).

The underlying cause of drought is a deficiency of precipitation. Wilhite and Glantz (1985) found numerous definitions of drought and grouped them into four major categories: meteorological, agricultural, hydro-

logic, and socio-economic The definition used historically in New Zealand was a meteorological one – defining droughts in terms of duration of days without rain (Bondy, 1950).

A meteorological drought was defined as a period of 15 days with no measurable rain ( $<0.1$  mm /day) and a dry spell as a period of 15 days with no more than 1 mm of rain each day. In practice, the commencement of drought is not easy to define. Thompson (2006) used a drought severity index of Phillips and McGregor (1998) which is based on the precipitation deficit-index of Bryant et al. (1992), and uses monthly precipitation anomalies to monitor rainfall surpluses and deficits. They develop slowly, spread amorphously, and then end when ample rainfall occurs.

However, other common drought types (agricultural, hydrologic and socio-economic) place greater emphasis on human or socio-economic aspects of drought, featuring the interaction between the natural characteristics of the event and human activities dependent on precipitation to provide adequate water supplies. These illustrate that drought is not simply a meteorological phenomenon, but is a term used more broadly to describe a shortage of water that impacts on any end use. Drought occurs whenever the supply of moisture from precipitation or stored in the soil or hydrological reservoirs is insufficient to fulfil the optimum water requirements of plants, water supply for urban dwellers, inflows into hydro lakes or some other purpose. Agricultural drought is more commonly defined by the availability of soil moisture to support crop and pasture growth. Soils vary in their water holding capacity. Hydrological drought is normally defined in terms

of surface and subsurface water supplies compared to some average conditions.

Because of New Zealand's complex orography, the characteristics of a drought reflect the interaction of persistent synoptic weather and larger scale climate patterns such as the El Niño/Southern Oscillation (ENSO) and topography. They therefore tend to be regional in extent. Salinger(1995), as suggested by Bondy (1950), who identified three principal drought prone regions by subdividing the country into areas of similar seasonal variation in drought susceptibility;

The west of the North Island and north east of the South Island. Droughts are most frequent in summer, particularly in February, when anticyclonic conditions are affecting the North Island.

The east of the North Island. The predominance of westerly quarter airflow is an important mechanism for this region and droughts are prolonged when westerly winds predominate. This is particularly the case in El Niño years, when droughts typically reach their maximum intensity in early summer.

Central Canterbury to inland Otago. In this drier region anticyclones tracking slowly over southern New Zealand, referred to as 'blocking anticyclones', are an important mechanism. As these are most frequent in the winter, droughts can be persistent at this time of year.

As agricultural drought normally has the most widespread impacts, it is useful to examine patterns of agricultural drought. Definitions of drought and water availability for agriculture have varied over the years in New Zealand. From the 1940s to the 1960s drought relief for farmers

was considered when rainfall at a representative rainfall station in a drought affected area for a consecutive three-month period was at a one in 20 year minimum. From the late 1960s the ‘days of deficit’ (Maunder, 1966) measure was developed in New Zealand (Coulter 1973, Maunder 1977). This measure is one that is based on soil moisture. The soil is assumed to have an available water capacity (AWC) (New Zealand Meteorological Service, 1986; Porteous et al. 1994) for plant growth, when holding the maximum amount of water the soil is said to be at field capacity. Conversely, when a plant has removed all the moisture through evapotranspiration, it is said to be at wilting point. The AWC is the difference between the amount of soil moisture at field capacity and at wilting point. Once the AWC is exhausted and the soil is at wilting point, the counts of ‘days of deficit’ commence. Salinger (1995) suggested that the pattern of agricultural drought can be indicated by the average number of days at wilting point (average annual water deficit). Recently, Porteous (2004) has comprehensively reviewed agricultural drought definitions and this paper will utilize an index recommended by Porteous (2004) for quantitatively defining drought.

The paper will define coherent regions of New Zealand within which there is a similar response to the interaction between circulation and orography, so as to define districts of agricultural drought over the period 1941 - 2013. Links will be made between drought occurrence and time series of indices of atmospheric circulation (Trenberth, 1976, Salinger and Mullan 1999) and synoptic weather types (Kidson, 2000).

## 2. Data and Methods

### 2.1 Selection of Drought Index

In global assessments of trends in drought over the past 60 years the Palmer Drought Severity Index (PDSI) has been used. However, a new assessment of drought trends over the past 60 years finds little evidence of an expansion of the area affected by droughts, contradicting several previous estimates (Seneviratne, 2012; Sheffield et al. 2012; Trenberth et al. 2014). This is because the PDSI method does not use the Penman–Monteith formulation for evapotranspiration, and tends to overestimate the drying trend. Other explanations for a disparity in trends lie in the difference in primary global precipitation datasets available and the role of natural variability (Trenberth et al. 2014).

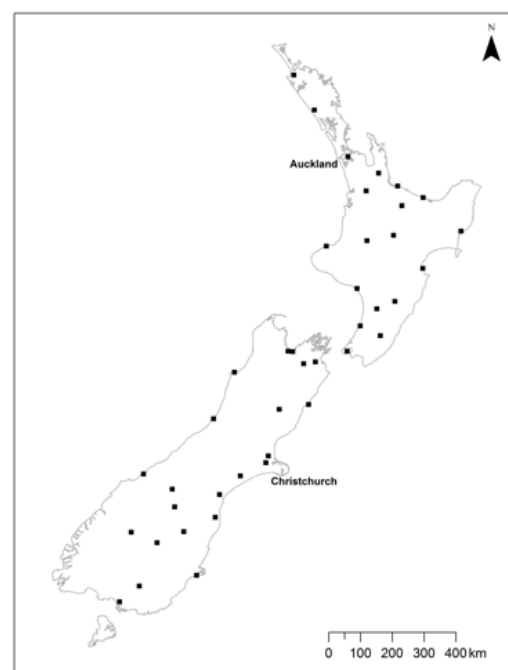
Porteous (2004) recommended a number of criteria in deciding on a suitable drought index for agriculture. Such a measure should be applicable to the entire country, be easily interpreted, supported by readily available data to enable robust calculation of anomalies and statistics, indicative of production losses and be representative of both the duration and intensity of the drought. Salinger (2003), Porteous (2004) and subsequently Mullan et al. (2005) recommended the ‘potential evapotranspiration deficit’ (PED) accumulated over a July to June ‘growing year’ as a measure of drought, using the Penman-Monteith approach to estimate daily evapotranspiration. This measure integrates the affects of rainfall and evapotranspiration (referenced to pasture) and is the amount of water than would be required to be added by irrigation to a crop or pastures over a year to avoid production loss. The PED is approximately equivalent to

the amount of water that is required to sustain pasture growth. A season with high PED will have reduced pasture production, and a season with low PED will have increased pasture production for rain fed agriculture.

The National Institute of Water and Atmospheric Research (NIWA) Climate Database was searched for New Zealand stations whose records were complete, or near complete for the 1941/42 – 2012/13 period. PEDs were accumulated daily over the July to June growing season, where PED is the accumulated difference between potential evapotranspiration (PET) and precipitation, beginning from zero each year. Nineteen North Island and 22 South Island stations (Figure 1) were used. In most cases an approximately equal area grid of stations was obtained, but coverage in the more remote mountainous areas of New Zealand was more difficult to achieve.

## 2.2 Principal Component Analysis

Principal component analysis (PCA) has been very successfully applied to climate time series (Craddock and Flood, 1969, Pittock, 1980a,b). Conventionally, unrotated components compute patterns where successive components are fitted to data to achieve maximum reduction in total variance. In this instance, the investigation was not directed toward accounting for the maximum possible PED variance by a small number of components, but rather to investigate the spatial distribution that occurs. The principal components are rotated around the origin until each is maximally collinear with a distinct cluster of vectors. The shift is then from components that maximise variance to components delineating separate groups of highly correlated stations for analysis of drought variation.



**Figure 1.** Map of New Zealand showing the 41 sites used to analyse PED from 1941/42 to 2012/13

A rotated principal component analysis was carried out on the seasonally accumulated PED to identify characteristic patterns of drought variation. A set of unrotated principal components was first calculated. A varimax rotation, that retains orthogonality between components, was then performed. The number of components rotated was decided by the usual criteria (Kaiser, 1960; Craddock and Flood, 1969), where unrotated components beyond the cut-off accounted for a very small proportion of the relative variance. Retaining these higher components did not produce additional patterns with high correlations for any site. The PCA analysis was performed on the full 41 station data set, as well as separately for the North and South Islands. The latter analyses were performed to confirm the stability of the New Zealand wide patterns, and relationships with circulation and weather types.

To interpret the rotated principal component (RPC) patterns of drought each pattern was related to circulation variations using correlations. Correlations were calculated between RPC scores for each season and the various circulation indices (Trenberth, 1976; Salinger and Mullan, 1999), generally over the period of record, and seasonal frequencies of Kidson (2000) synoptic types from 1948/49 – 2012/13. After exploratory analysis, the period October – March was selected for each growing season, as this is the period of high PED accumulation. Trenberth (1976) defined four zonal and three meridional airflow circulation anomalies over New Zealand, and Salinger and Mullan (1999) extended these (Table 1). Kidson (2000) identified twelve characteristic synoptic weather types (Table 2) which group into three regimes characterised by (i) frequent troughs crossing the country (four), (ii) anticyclones to the north with strong zonal flow to the south of New Zealand (three), and (iii) blocking patterns with anticyclones more prominent to the south (five). As well, correlations were performed with the Southern Oscillation Index (SOI).

### 2.3 Time Series Analysis

The RPC scores were retained for the full New Zealand data set for the first five RPCs. These were averaged for the five New Zealand wide patterns as a measure of year to year drought variability nationally, with positive scores representing the drier years, and negative scores representing the wetter years. This was used as a tool to rank the years with highest and lowest PEDs overall. For each of the RPC patterns, the component scores were also plotted for trends of regional drought.

### 3. Rotated Principal Component (RPC) Results

For the New Zealand wide analysis, only the first five RPCs were retained, because these explained 69% of the variance. (Table 3) These all had eigenvalues of 2 or more. The RPCs for New Zealand are now described in some detail, and related to circulation fluctuations and variability of weather types in the New Zealand region. Comments on associated circulation and weather types are based on Tables 4 and 5, which show correlations between seasonal RPC scores and the circulation indices and weather types. Many of the indices listed in Table 4 are themselves correlated, so the focus is on those indices displaying the largest absolute correlations with the RPC time series. For the circulation indices, in most cases there is a direct and straightforward physical link between the index and the PED pattern in terms of airflow direction and its interaction with topography. For the weather types positive relationships indicate that the synoptic type promoted the PED pattern, whereas negative values indicate the reverse, i.e. lack of that PED pattern of dryness.

The PED RPC patterns are shown in Figures 2 to 6. The number of rotated components retained was five according to the criteria discussed earlier.

**NZ1.** NZ1 represents strong PED accumulations in the north of the North Island (Northland, Auckland, Waikato, Bay of Plenty) and accounts for 19% of the variance (Figure 2).

Correlations were highest with zonal flow across New Zealand, and when west to southwest flow with anticyclones occurred (HNW, SW).

Index	Definition	Wind anomaly (+/- index)
Z1	Auckland – Christchurch	West/east (central New Zealand)
Z2	Christchurch – Campbell Is	West/east (south of New Zealand)
Z3	Auckland – Invercargill	West/east (New Zealand)
Z4	Raoul Is – Chatham Is	West/east (east of North Island)
M1	Hobart – Chatham Is	South/north
M2	Hokitika – Chatham Is	South/north (east of New Zealand)
M3	Hobart – Hokitika	South/north (west of New Zealand)
MZ1	Gisborne – Hokitika	North north west/south southeast
MZ2	Gisborne – Invercargill	West/northwest/east-southeast
MZ3	New Plymouth – Chatham Is	Southwest/northeast
ZN	Auckland – Wellington	Westerly/easterly over the north
ZS	Wellington - Invercargill	Westerly/easterly over the south
SOI	Tahiti – Darwin	Northeast/southwest

The indices are calculated from monthly mean sea level pressure differences (using deviations from long-term monthly means), over the base period 1971-2000. Indices which do not start at or prior to 1930 are: Z2 (1941), Z3 (1948), Z4 (1940), MZ2 (1948) and MZ3 (1944).

*Table 1. Definition of circulation indices and corresponding airflow anomalies over New Zealand. (Trenberth (1976), Salinger and Mullan (1999)).*

Synoptic Type	Description
<b>“Trough Tr” Group</b>	
T	Trough over New Zealand
SW	Disturbed southwest flow over New Zealand
TNW	North/northwesterlies proceeding a trough over New Zealand
TSW	Southerly flow with trough over North Island
<b>“Zonal” group</b>	
H	Anticyclone west of North Island and westerly flow to south
HNW	Anticyclone in Tasman Sea with west to south west flow
W	Anticyclone over the north with westerly flow
<b>“Blocking” group</b>	
HSE	Anticyclone east of South Island
HE	Anticyclone east of North Island
NE	Anticyclone over Chathams and north east flow
HW	Anticyclone west of South Island and southerly flow
R	Ridge over South Island, easterlies over North Island

The synoptic weather types start in 1948.

*Table 2. Kidson synoptic weather types and weather regimes after Kidson (2000)*

RPC	1	2	3	4	5	Total
New Zealand	19.3	17.3	11.7	11.6	9.1	69.0

Table 3. Explained variance (%) of seasonal PED rotated principal components, for the period of analysis.

RPC	Z1	Z2	Z3	Z4	M1	M2	M3	MZ1	MZ2	MZ3	MZ4	ZN	ZS	SOI
NZ1	<b>34</b>	<b>34</b>	27	<b>32</b>	20	<b>39</b>	7	-20	13	<b>42</b>	21	<b>35</b>	12	-19
NZ2	<b>43</b>	<b>51</b>	<b>48</b>	14	-1	14	-7	14	<b>58</b>	24	13	<b>37</b>	54	-8
NZ3	<b>-54</b>	3	<b>-54</b>	<b>-42</b>	1	-5	3	-29	<b>-47</b>	-28	<b>-53</b>	<b>-55</b>	<b>-44</b>	<b>35</b>
NZ4	<b>-31</b>	5	-24	<b>-53</b>	<b>-51</b>	-21	<b>-49</b>	-9	-11	<b>-34</b>	<b>-34</b>	<b>-36</b>	-6	<b>37</b>
NZ5	-4	<b>32</b>	2	18	<b>34</b>	<b>52</b>	-16	<b>-59</b>	-18	<b>38</b>	-8	2	-8	-11

Cross-correlations of 0.30 are significant at the 99% level, and have been bolded.

Table 4. Correlation ( $\times 100$ ) of RPC scores with circulation indices October – March.

RPC	T	SW	TNW	TSW	H	HNW	W	HSE	HE	NE	HW	R	Tr	ZON	BLO
NZ1	8	<b>41</b>	-28	<b>-47</b>	26	<b>34</b>	<b>26</b>	-3	5	<b>-45</b>	-6	-4	-5	<b>37</b>	-23
NZ2	1	17	-16	<b>-41</b>	27	<b>35</b>	21	10	14	-16	-6	<b>-50</b>	-14	<b>36</b>	-13
NZ3	<b>-41</b>	-15	-28	-5	16	10	<b>-36</b>	<b>33</b>	0	12	<b>37</b>	24	<b>-43</b>	1	<b>42</b>
NZ4	<b>-33</b>	<b>-38</b>	0	-5	5	-18	-28	<b>49</b>	11	20	23	9	<b>-40</b>	-13	<b>50</b>
NZ5	-10	25	<b>-47</b>	3	14	23	10	-1	8	-25	14	-4	-9	20	-7

Cross-correlations of 0.30 are significant at the 99% level, and have been bolded.

Table 5. Correlation ( $\times 100$ ) of RPC scores with synoptic weather types October – March.

This indicates that high PED seasons occur with anticyclones in the Tasman Sea and west or southwest flow prevails. Conversely, weather types bringing northeasterlies over the North Island (NE) and southwesterly troughs

(TSW) produced seasons with low PED accumulations.

**NZ2.** This pattern, representing PED centred on the east of the South Island, extends from central and coastal



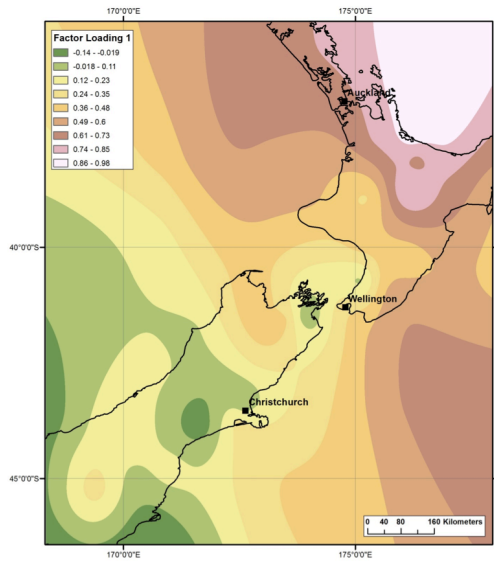


Figure 2. New Zealand accumulated seasonal PED rotated component patterns (RPC's) 1 for the time period 1941/42 – 2012/13. The explained variance is 19.3%, along with the number of the rotated eigenvector described in the text.

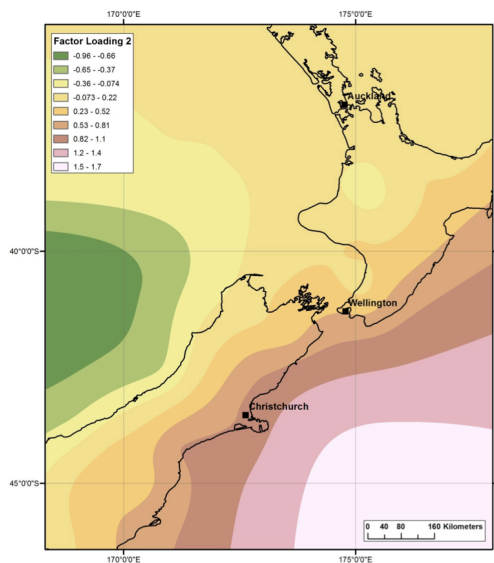


Figure 3. As for Figure 2, but for RPC 2. The explained variance is 17.3%.

Marlborough to Dunedin (Figure 3). It accounts for about 17% of the variance. Correlations were highest with indices of southwest flow over New Zealand (M2 and MZ3) and moderate with the zonal flow group. This was confirmed by the relationships with synoptic types,

HNW producing anticyclones with west to northwest flow, correlations with these weather types being positive. Thus west to northwest flow leads to high PED. The converse, north to northeast flow and ridges to the south, led to low PED in this region. Southerly troughs (TSW) also produced low PED seasons.

**NZ3.** PED NZ3 denotes dryness in southern New Zealand (Figure 4). The

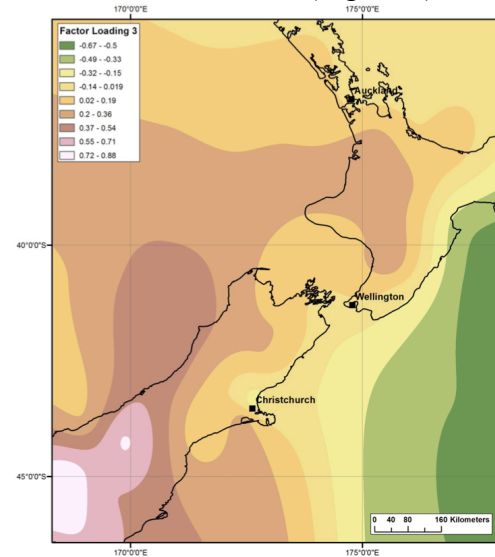


Figure 4. As for Figure 2, but for RPC 3. The explained variance is 11.7%.

highest station loadings occurred in central and eastern Otago and Southland, and accounted for about 12% of the variance. Significant negative correlations occurred with zonal October – March circulation indices, and positively with the Southern Oscillation Index, together with Kidson circulation type HW, and the blocking regime. This indicates increased PED in La Niña years when east or northeast circulation and more frequent anticyclones prevail. Wet years are associated with El Niño events, with more enhanced westerly circulation, and in seasons with more troughs and westerly (T, W) Kidson weather types.

**NZ4.** NZ4 has its highest station loadings in the southwest of the North

Island, and includes parts of the Wairarapa (Figure 5). The strongest negative correlations were with Z4, which represents easterly flow east of

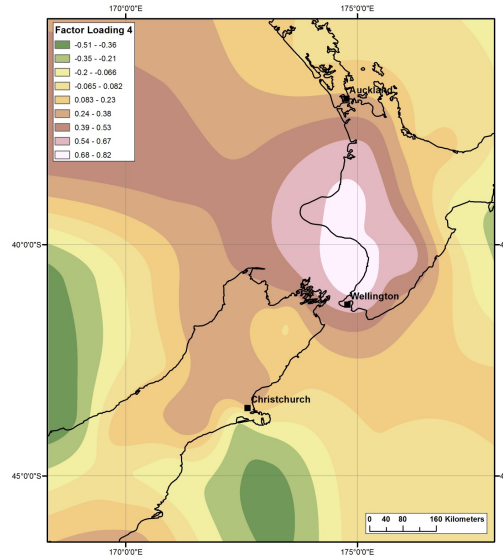


Figure 5. As for Figure 2, but for RPC 4. The explained variance is 11.6%.

the North Island. Of the synoptic types, anticyclones east of the South Island (HSE) produced high PEDs, together with the blocking regime. Low PEDs occurred with westerly troughs and south westerlies (T, and SW regimes and Tr group) in strong westerly flow over the North Island. The pattern accounted for about 12% of the variance.

**NZ5.** NZ5 shows highest loadings in the north of the South Island, and to a lesser extent in inland Canterbury (Figure 6). This pattern explained 9% of the variance. Significant correlations occurred with M2 and MZ1 indicating higher PED seasons occur when south to southeast flow is more dominant. These relationships were confirmed by the synoptic types: the southwest flow type over New Zealand (HNW). Low PED seasons

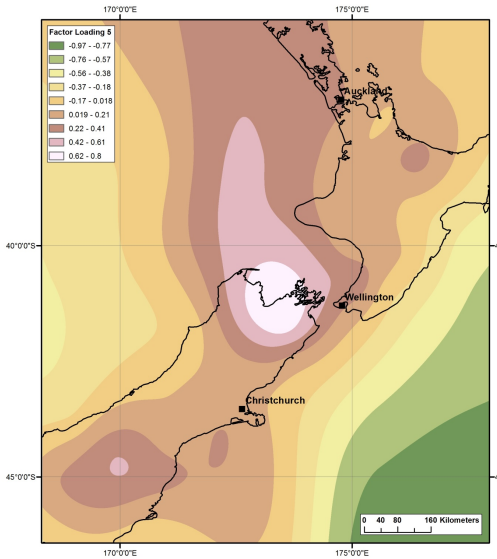


Figure 6. As for Figure 2, but for RPC 5. The explained variance is 9.1%.

were produced by troughs in northwesterlies (TNW).

4. Variability

When the five pattern scores were averaged 2007/08 ranked as the most severe (Table 6), followed by 2012/13, 1977/78 and 2000/01. The time series of the averaged five pattern scores show an increase over the 72 year period (Figure 7); trending towards a run of higher PED seasons since 1997/98. This trend towards increasing PED seasons is seen in all of the regions (Figure 8) except NZ4 (western North Island). The ‘wettest’ years (lowest PED) in decreasing order are 1944/45, 1957/58, 1979/80 and 1952/53 (Table 6).

High	Low
2007/08	1944/45
2012/13	1957/58
1977/78	1979/80
2000/01	1952/53
1972/73	1985/86

Table 6. Ranking of high and low PED years, average of five patterns

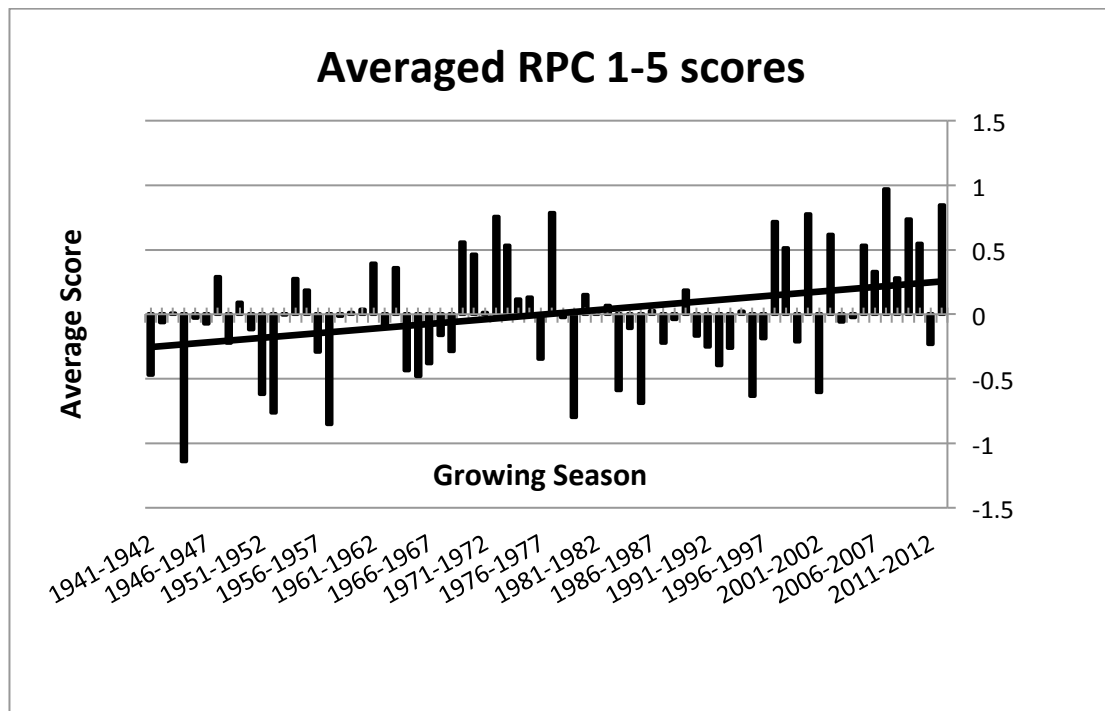


Figure 7. Time series of July-June seasonal PED for the five pattern scores averaged for New Zealand, expressed as anomalies over the 1941/42-2012/13 analysis period.

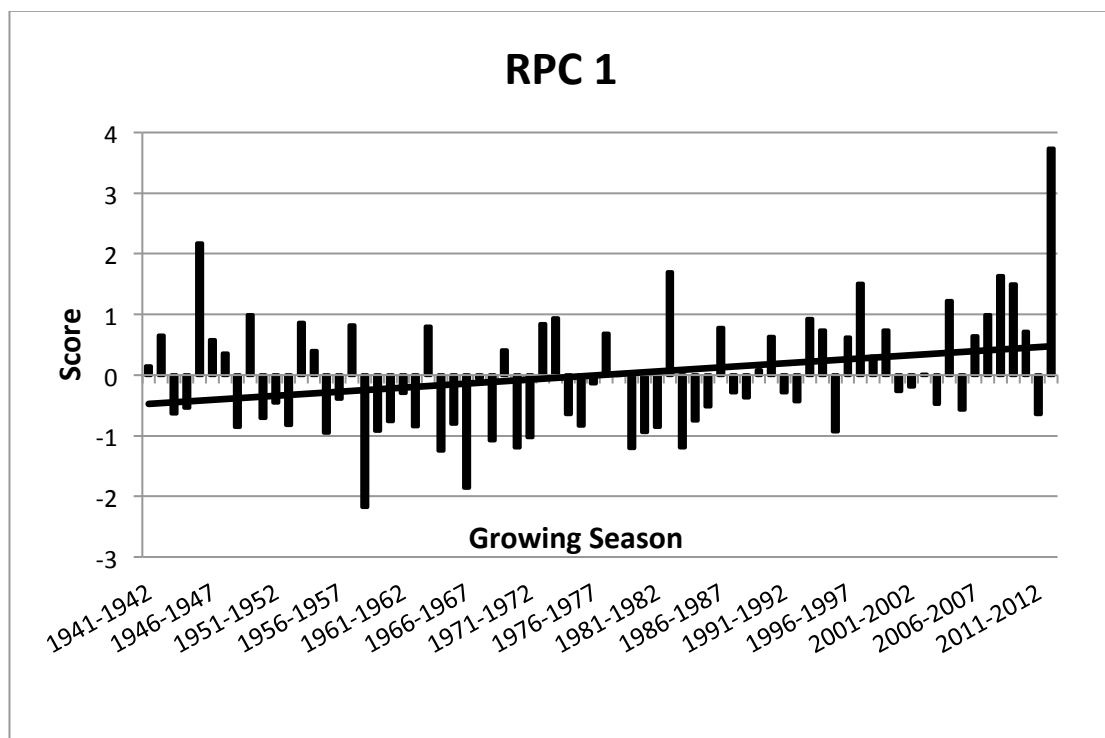


Figure 8. Time series of pattern scores for each of the RPCs over the 1941/42-2012/13 analysis period, with a linear trend plotted.

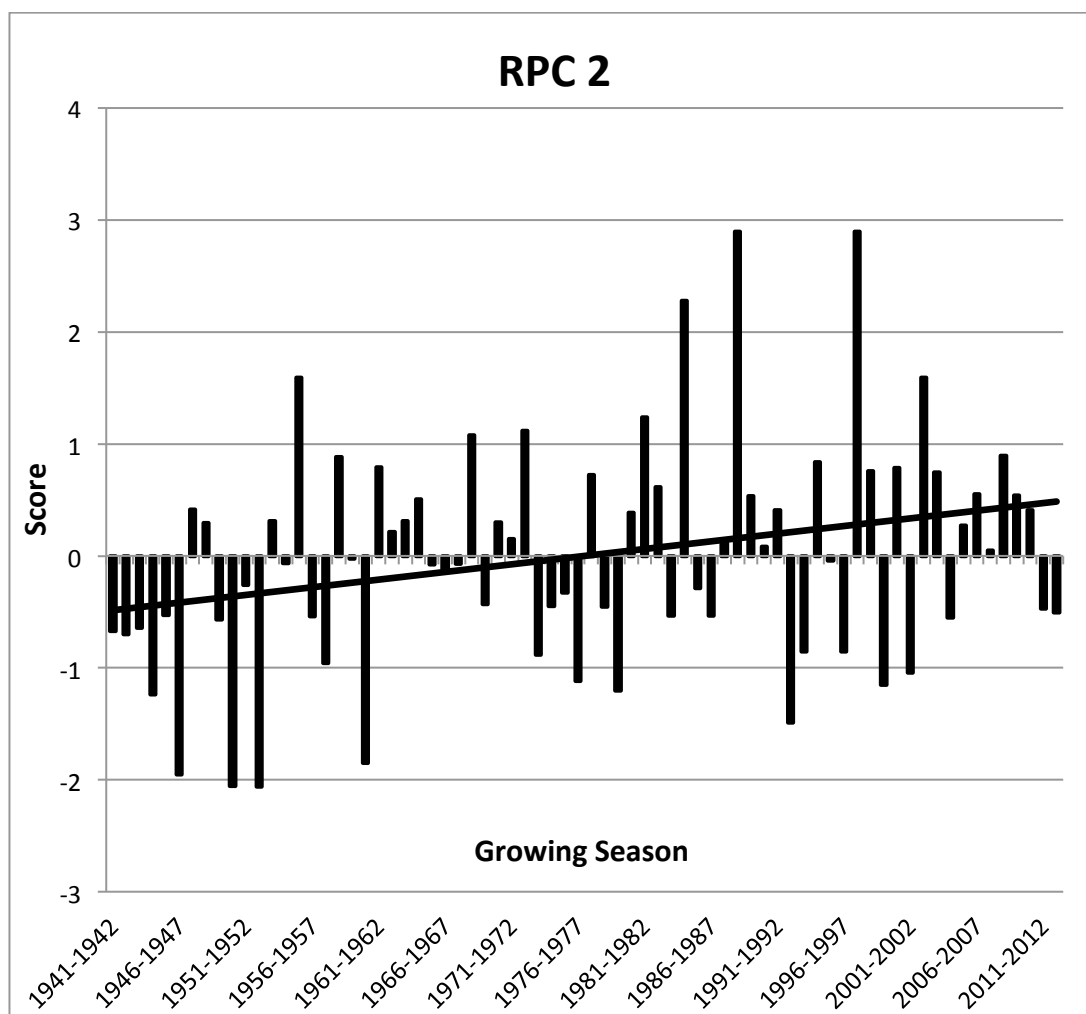


Figure 8 continued.

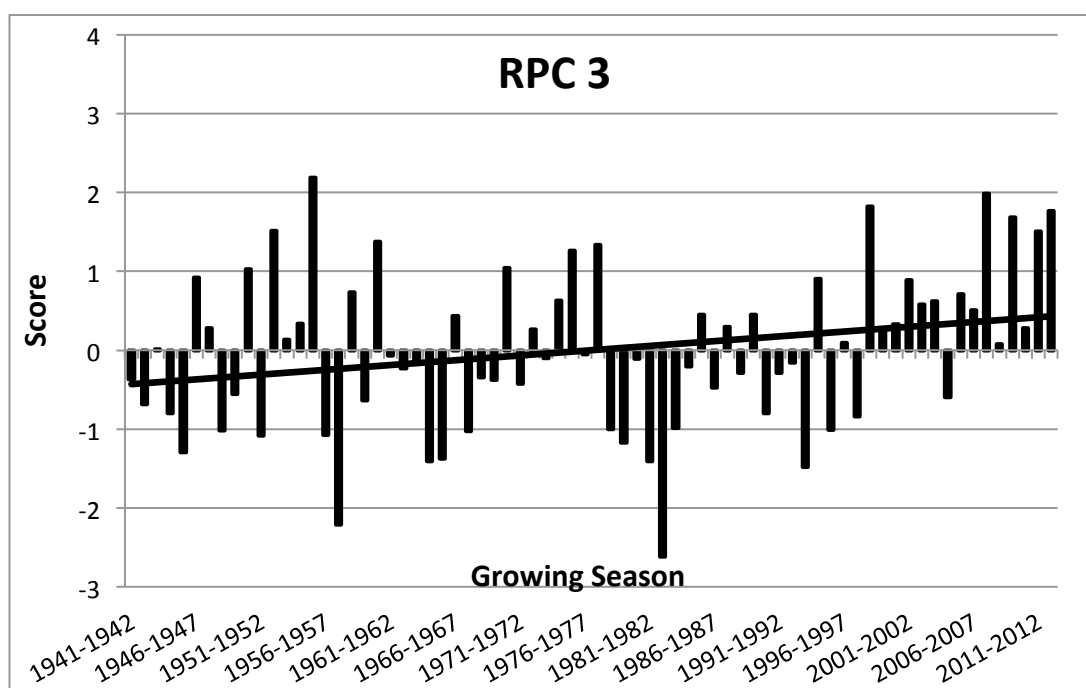
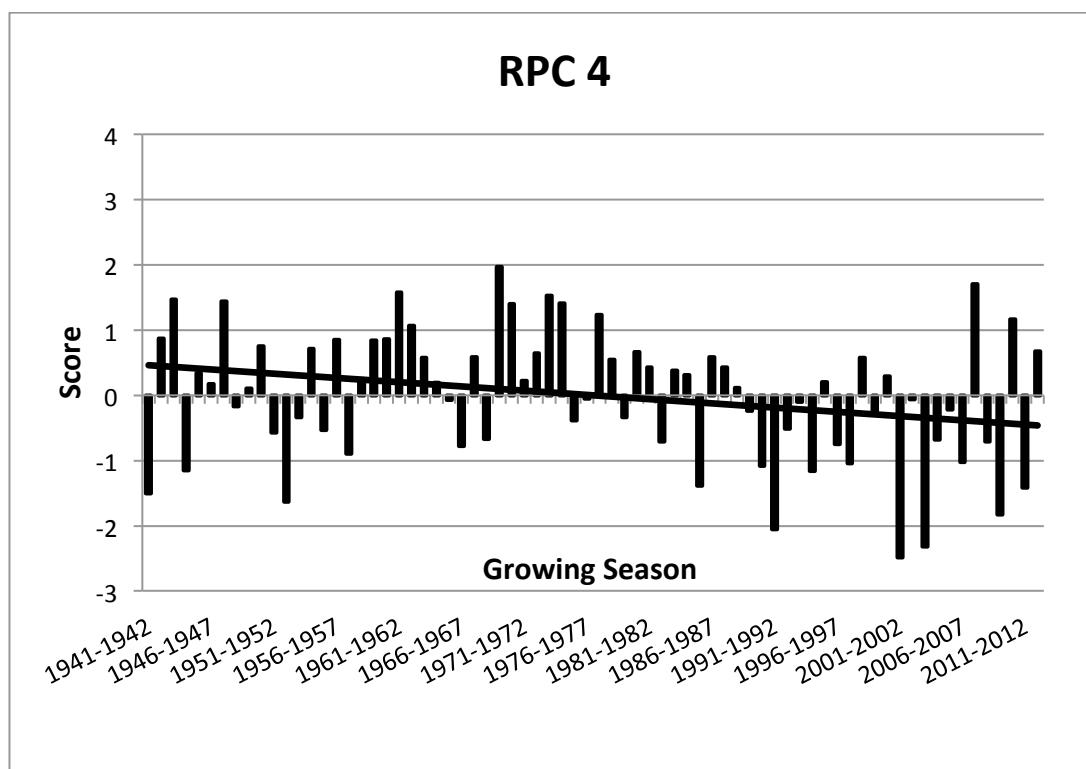
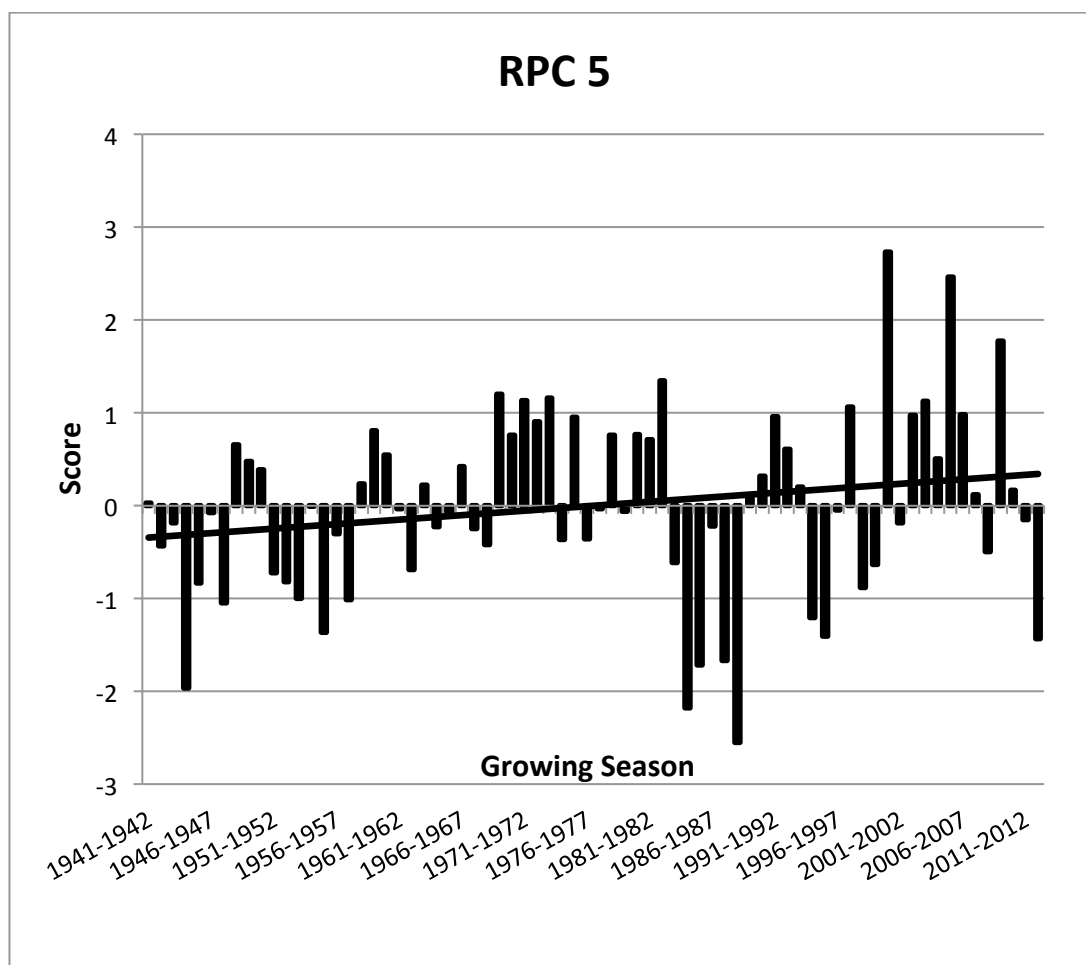


Figure 8 continued.

*Figure 8 continued.**Figure 8 continued.*

## 5. Discussion and Conclusions

The analysis presented in this paper has defined five regions of New Zealand within which periods of agricultural drought appear to be spatially coherent. Accumulated 'potential evapotranspiration deficit' (PED) accumulated monthly over the July to June growing season from daily data stored in the NIWA climate database was used as the index of agricultural drought. In the drier areas of New Zealand rainfall does not satisfy the atmospheric demand on pasture systems to transpire and evaporate water because there is not enough rain during key growth phases. In more humid areas of the country, over the summer season or during dry seasons, rainfall is not sufficient to meet PET. For example, PEDs in dryland areas of New Zealand (Salinger 2003) typically reach between 300 and 500 mm over the growing season. This would be the amount of water that would be required for application to sustain pasture or crop growth for optimum production over the growing season. The PED, as a measure of both the 'depth' of the rainfall deficit, and its accumulation over time (e.g. a season), can be used to describe both the intensity and the duration of agricultural drought.

Five coherent regions for spatial patterns of PED were yielded for New Zealand: the north of the North Island, the east of the South Island, the south of the South Island, the west of the North Island, and north of the South Island. Similar spatial regions were identified in the separate island analyses.

The quantitative analysis identified that these five regions do not compare so well with some of the three drought regions initially identified by Bondy

(1950). Eastern areas of the North Island were not strongly identified in NZ1 (the north), NZ2 (the east) and NZ3 (the south). The southeast of the South Island was consistent with NZ3, although Bondy (1950) extended this region further north. However, Bondy's (1950) classification amalgamated the north and west of the North Island together with the north and east of the South Island. The examination here has characterised these into four regions: the north of the North Island, the north of the South Island, the west of the North Island, and east of the South Island. Finally, Bondy (1950) did classify an area which was not drought prone: the west of the South Island.

New Zealand's orography plays a major role in determining the spatial response of regional rainfall anomalies to patterns of circulation (Salinger, 1980). Anomalies linked to persistence of particular circulations or increased frequency of synoptic types will typically either increase or reduce PED in definable regions of New Zealand. Generally a persistence of anticyclones somewhere in the New Zealand region was favourable for the development of above average PEDs. Conversely, the occurrence of troughs more frequently led to low PEDs.

More frequent anticyclones in the Tasman Sea with a predominance of southwest flow were the common feature for seasons with high PED in the north of the North Island. The converse, troughs and north or northeast flow anomalies gave seasons with low PED. For the east of the South Island anticyclones and west to southwest flow seasons were important in producing high PEDs, and easterly flow low PEDs. For southern New Zealand stronger easterly flow anomalies were important for dry seasons. For the west of the North Island seasons with

drought (high PED) showed a prevalence of more anticyclones east of the South Island and easterly flow anomalies. Wetter seasons showed more troughs and westerlies over the North Island. The fifth pattern, high PEDs in the north of the South Island and inland Canterbury, was associated with south to southwest flow, with low PED seasons occurring in years with more frequent troughs with northerly Kidson weather types.

The spatial patterns of drought have been ranked overall for examination of any trends. These patterns favour the north and west of the North Island, and north and east of the South Island. The five years that ranked the highest in terms of the drought index nationally were 2007/08, 2012/13, 1972/73, 2000/01, and then 1977/78. In an earlier analysis by Mullan et al. (2005) using a grid point Virtual Climate Station Network (VCSN) for the shorter period 1972/73 to 2002/03, 1972/73 and 1977/78 ranked the highest. Of the 1972/73 event, Waugh et al. (1997) noted that a major drought occurred in South Canterbury, Northland, Taranaki and Nelson areas. These two events show significant losses in agricultural production (Ministry of Agriculture and Forests, 1998). Updates by NIWA (Blackman, 2013; NIWA, 2013) used PED calculations, derived for the months of July to May, were applied to selected long-period station observations, back to the early 1940s, and also using NIWA's VCSN from 1972. Both analyses show that the 2012–13 drought was one of the most extreme on record for New Zealand. For much of southern Northland, Auckland, Waikato, Bay of Plenty, Gisborne, Hawke's Bay, and West Coast, the July 2012–May 2013 PED accumulation was the largest in the 41-year VCSN record. The longer-record station calculations indicate

that an event of similar severity occurred in the 1945–46 season.

Conversely, the three seasons 1944/45, 1957/58 and 1979/80 ranked as the lowest for PED across the country. Only the last is covered by Mullan et al. (2005) and this is the lowest for PED from the grid point VCSN data series for the period 1972/73 to 2002/03.

This paper has shown that there are large areas of New Zealand where agricultural drought is spatially coherent. Five regions have been defined covering the country, with three in the South Island and two in the North Island. The patterns are very sensitive to the persistence of atmospheric circulation anomalies, and for most of the regions, more anticyclones than normal in the New Zealand region.

Attribution of the cause of the 2012/13 event (Ministry of Primary Industries, 2013) was tracked through an austral summer high pressure index - by averaging the December–February pressures from six long-term recording sites: Auckland, Wellington, Hokitika, Christchurch, Chatham Islands, and Hobart. This shows a statistically significant trend over the 1911 – 2013 period, to an increased summer high pressure index. In the 2012/2013 summer the persistence of slow-moving or 'blocking' high pressure systems over the Tasman Sea and New Zealand was very marked.

In some regions seasons with more troughs than normal were responsible for a low occurrence of drought. The results show that, for such patterns to occur, certain weather types must persist in the New Zealand region on a seasonal basis. Despite New Zealand's maritime location, and hence the inherent variability in synoptic scale

weather patterns, seasons do occur when there is persistently anomalous atmospheric circulation, or an increased predominance of particular synoptic weather types. Both can lead to seasons with higher PEDs than normal.

Explanations of the longer term trend in the austral summer (December – February) precipitation are seen in the response of the Southern Hemisphere to stratospheric ozone depletion in the 20th century. Fyfe et al. (2012) note a mid-latitude drying and high-latitude moistening, which are closely consistent

with trends simulated in response to historical changes in anthropogenic and natural forcing by anthropogenic greenhouse gas and ozone changes, with an opposing influence from aerosols. Similar results are obtained from the multimodel output from the Climate Model Intercomparison Project 3 (CMIP3) by Purich et al. (2012). The latter show that Antarctic ozone forcing significantly modulate the decrease in mid-latitude precipitation. Grise et al. (2014) notes that ozone depletion in the late 20th century induced a significant poleward shift in cyclone frequency over the Southern Ocean. A poleward shift in the tropospheric mid-latitude jet or the Southern Annular Mode (SAM) has also occurred (Previda et al. 2014). The SAM changes in surface climate in New Zealand (Thompson et al. 2011) show a weakening of westerly circulation during the austral summer. The warming trend in the New Zealand region (Salinger 2012) will increase PET, and, associated with the austral summer higher pressures has led to the drying and increased PED in four of the five RPC regions.

Future climate scenarios by NIWA (2005, 2011) based on models warming under increasing greenhouse

gas forcing predict that the tropics will effectively ‘expand’. The sub-tropical high pressure belts enlarge and with an associated reduction in precipitation (Trenberth, 2011). For agricultural regions projections suggest that key eastern regions are more likely to spend about ten percent additional time spent in drought by the middle of the 21st century. NIWA (2011) finds that by the end of the 21st century the projections suggest that most of the country’s agricultural regions will experience some increase in drought, even under milder climate scenarios.

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